Minerals **2013**, *3*, 304-317; doi:10.3390/min3030304

OPEN ACCESS

minerals

ISSN 2075-163X
www.mdpi.com/journal/minerals

Review

Sustainability of Rare Earths—An Overview of the State of Knowledge

Benjamin C. McLellan [1,2,*], Glen D. Corder [2] and Saleem H. Ali [2,3]

1 Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan
2 Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, St Lucia, QLD 4072, Australia; E-Mails: g.corder@smi.uq.edu.au (G.D.C.); s.ali3@uq.edu.au (S.H.A.)
3 Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05401, USA

* Author to whom correspondence should be addressed; E-Mail: b-mclellan@energy.kyoto-u.ac.jp; Tel.: +81-75-753-9173; Fax: +81-75-753-4745.

Received: 7 July 2013; in revised form: 16 August 2013 / Accepted: 3 September 2013 / Published: 10 September 2013

Abstract: Rare Earths (RE) have been the focus of much attention in recent years as a consequence of a number of converging factors, prominent among which are: centralization of supply (in China), unique applications in high-end technologies particularly in the low-carbon energy industry, and global demand outstripping availability. Despite this focus, RE supply chain sustainability has not been examined in depth or in any systematic manner. This paper provides an initial review of RE sustainability considerations at present, including current initiatives to understand the research and development needs. The analysis highlights a broad range of areas needing consolidation with future research and calls for collaboration between industry and academia to understand the sustainability considerations of these critical elements in more depth.

Keywords: rare earths; sustainability; social; environmental; energy

---

1. Introduction

Rare Earths (RE) have been of considerable interest in recent years for a variety of reasons, in particular due to concerns over the security of supply for modern high efficiency electronics and energy technologies. Such concerns have placed them among the list of "critical" or "strategic" elements in countries such as the United States of America (USA) [1–4], the European Union (EU) [5,6], Japan [7] and even in the largest producer and holder of reserves, China [8]. One article has reported on RE contribution to sustainable development from their importance as "critical materials", but did not delve broadly into sustainability implications, focusing on the techno-scientific elements, scarcity and economics [9]. Much focus has been given to the environmental impacts of production, and on the distribution of reserves and politico-economic conflict over supply, but there has been limited international academic work that quantifies these impacts. Moreover, to the authors' knowledge, there is no expanded consideration of sustainability impacts and benefits in a structured and holistic manner—particularly in regard to the social impacts of RE extraction, processing and utilization.

By way of definition, the remainder of this paper considers sustainability within the frameworks of mineral resources as: "a state of dynamic interplay between environment and society (in a broad sense) that ultimately contributes positively to indefinite human development and universal wellbeing whilst not overdrawing on natural resources or over-burdening the environment in an irreversible manner. When we use the term sustainability in mining, for example, we don't mean mining that can be 'sustained' but rather we mean a mine that is making its proper contribution to societal sustainability." (after [10,11]). Due to the lack of specific literature on RE in relation to sustainability or sustainable development specifically, this paper has taken the approach of dividing the literature into four categories of environmental, economic, social and techno-scientific aspects. The first three of these categories follow the widely used approach of the triple-bottom-line (TBL). However, it is also acknowledged that more literature is not specifically examining any of these categories, but is focused on the technological and scientific aspects of RE. This literature also contributes to understanding RE within the framework of sustainability, as it enables an understanding of the markets and benefits that RE may contribute. Without understanding these techno-scientific aspects, it is impossible to truly examine RE sustainability.

In response to the apparent gap in knowledge, this paper undertakes a first-pass review of the literature and state-of-play of sustainability assessment of rare earth elements. It is expected that this will be further expanded through new collaborative research between industry and academia.

2. Results

The literature regarding RE was extensively reviewed, with the consideration of sustainability across the supply chain of these elements as the primary focus. The focus was placed on examination of literature covering four associated categories: technical, environmental, social and economic aspects of RE supply chains. These four areas combined give an indicative picture of the state-of-play in considering a variety of sustainability impacts of RE. Only English language literature was addressed in this study.

2.1. Techno-Scientific

A large proportion of RE research is devoted to the technological or scientific aspects of their extraction, processing, utilization and reprocessing or recovery—that is, to their application in technology, their thermodynamic, chemical and physical properties and the influence of these in a variety of operations or situations. There is much experimental work being done to determine key thermodynamic, physical and chemical properties of individual RE, as complexities in obtaining pure samples and measurements errors due to the properties of RE have hindered accurate assessments [12]. The applied techno-scientific literature is of most interest in this case, as it has the most direct influence on technology used in the industry at present and the near future.

The extraction of rare earths from ore and their separation is an area of intense focus—both due to the complexity and intensity of processes required (due to the similarity in chemical properties of the RE elements) [13], as well as the human health and environmental impacts (actual and potential) associated with the reagents and tailings [14]. A recent review of rare earth element bearing minerals summarized the main beneficiation methods as gravity, magnetic, electrostatic and flotation separation techniques [15]. Interestingly, the authors noted that the existing literature on the physical beneficiation of rare earth minerals mainly concentrates on two major rare earth element mineral deposits, Bayan Obo in China and Mountain Pass in USA. While acknowledging considerable rare earth research has been reported in Chinese journals, they noted that there was a lack of the requisite background information (proper chemical names of collector molecules, detailed descriptions of processes, *etc.*) to provide any significant insights into the development of separation processes for alternative rare earth minerals. These observations are part of the reason why there has been recent increasing interest in examining and researching new methods for the extraction and processing of rare earths.

Many individual researchers have been working for some time on ways of improving hydrometallurgical [16] and pyrometallurgical processes for RE extraction and separation. Hydrometallurgical processes rely on the ability to differentially extract and separate RE mixtures by varying the pH and acid/bases utilized. Solvent extraction is widely used, and has progressed as a preferred technique due to its simplicity, applicability to various concentration ranges and purity of products [17,18]. Alternative processes using supercritical fluids such as CO_2 have also been widely examined [19,20]. Moreover, interest in the extraction of RE using microbial [21] or other biological or enzymatic processes is growing, due to their potential for lower intensity processing and reduced environmental emissions.

Recently a number of major studies have been completed, reviewing progress in the recovery of RE via recycling of low value waste streams such as bauxite residue, phosphogypsum, waste water, slag and mine tailings [22–24]. Other authors have focused specifically on the waste from RE operations, which can hold significant amounts of unrecovered RE—especially in tailings from older, less efficient operations [25]. While ongoing interest in recycling of end-of-life batteries [25,26], computer monitors [27] and magnets [28] has shown some promise at the laboratory scale, with recoveries up to 96% of RE [29] and significant industrial investment in Japan and Europe has been made, with a number of new recycling plants recently announced or constructed it has yet to become widespread and suffers from the lack of collection facilities and recycling culture. The techniques for extraction and purification of RE in waste streams are largely the same as those utilized in processing primary ore—acid leaching [27], solvent extraction [26,30] and pyrometallurgical processes being commonly examined [22], with growing interest in ionic liquids as an alternative method [30,31].

The end-use applications of RE are indeed the key underlying reason for the heightened interest—particularly the linkage with energy technologies such as photovoltaics (PV) [32–34], wind power (magnets in generators) [35,36], in batteries useful for electric vehicles and renewable energy storage [26], in energy efficient devices such as light emitting diodes (LEDs) [32] and fuel cells [37]—all of which are considered as important elements in clean energy futures. RE have been used increasingly since the emergence of RE permanent magnets in the late 1960s [38] due to their particularly valuable functional properties. However, as demand overtakes supply, there is also significant research into alternative materials or processes (for example, alternatives to permanent magnets in motors [39]) to avoid vulnerability associated with a lack of physical availability due to production shortfalls in the short term or economic availability due to fluctuations in market price.

Therefore, in regards to the technical elements of RE sustainability, the utilization in high efficiency and clean energy technologies, and the improvement of recycling and waste reclamation are areas of clear importance. The improvement of extraction and processing or the discovery of low-impact alternatives are also of key importance for the future.

2.2. Environmental

The environmental component of sustainability is often highlighted in the discussions on RE technologies and processes—e.g., [14,32]—both as a positive in terms of clean energy and as a negative in terms of waste. However, it is much more difficult to identify accurate quantitative figures on any environmental aspects of RE. With regards to environmental research, the most progress has been in regards to the identification of mineral reserves (a tenuous use of the "environmental" term). In this area, discussion and data are relatively open [40–43]. With regards to this geological component of environmental and economic sustainability, one of the important points to note is that rare earths are not necessarily rare, but that the particular geological conditions that promote their concentration in sufficient levels to warrant extraction are rare. Therefore most rare earths have been extracted as by-products of other mined materials—iron ore or phosphorus, for example.

In regards to other environmental aspects, the situation is less clear. Some data on emissions and energy usage is becoming available through the environmental assessment procedures on new mining and processing facilities—e.g., Nolan's Bore [44]. Likewise, the recent focus on environmental impacts of RE extraction in China has provided some broad figures on the impacts of current processing—for example, the emissions of dust, sulfur compounds and fluoride (reported second hand in English) [45], and the environmental degradation due to leaching of RE deposits in China was highlighted as a significant issue [46]. Additionally, some new technology developers have provided a breakdown of water and reagent consumption [14] and estimates of usage rates of other reagents are given in discussions of China's policies [8].

Standard values for emissions and energy embodied in RE are not commonly available (apart from the rough estimates above), making environmental assessment in end uses inaccurate if not impossible. Moreover, the large range of elements considered (14–17 elements) and the highly complex, interconnected flowsheets required mean that life cycle analysis and the allocation of impacts is challenging. Likewise, each deposit is unique in its specific balance of RE, making the allocation to each element additionally challenging.

A cradle-to-gate life cycle assessment of rare earth elements produced in Bayan Obo, China, concluded that mining and beneficiation has much lower energy and material consumption compared to the other stages—separation of rare earth oxides and reduction to rare earth elements[47]. Furthermore, the life cycle assessment results showed that the high environmental impact of rare earth elements (on a per kg basis) coupled with low yield and low abundance provided a sound incentive to investigate recycling and recovery of rare earths or minerals that contain rare earths. The scope of the study was also limited in the terms of both major and auxiliary processes that were examined. This was one of the only studies to quantify the environmental impacts across the life cycle, although, as mentioned in the previous paragraph, the allocation of impacts was not trivial and was determined through a formula based on prices of rare earth elements. This illustrates how the allocation approach and/or assumptions used in the life cycle assessment play an important part in accounting for environmental impacts of individual rare earth elements.

The move to increase recycling and recovery of waste streams—both post-consumer electronics, municipal solid waste [48] and industrial waste streams such as coal fly ash [49]—has been driven largely by concerns about supply, but also with the intention of reducing environmental burdens over the life cycle of RE products. However, the techniques currently employed are largely similar to the techniques used for extraction from raw ore, and it is as yet uncertain whether the potentially-lower complexity of these waste streams will facilitate significant overall benefit. Moreover, in the case of coal fly ash for instance, it is important to consider whether RE can be extracted without negating the ability to use the waste in other valorizing industries—such as in the cement industry [50]. Other unconventional ore deposits—such as deep ocean deposits [42,51]—have clear technological challenges and unclear environmental impacts, making the comparison with conventional resources difficult.

Another key environmental issue that has led to substantial community concern, is the fact that radioactive elements thorium and uranium are often associated with RE deposits, and are one of the key issues with processing and disposing of waste. In sufficient quantities, Uranium can be recovered and utilized as nuclear fuel however, Thorium has been a problem as it is not currently utilized for power generation—although it has long been posited as both a useful nuclear fuel and as a way to get rid of such waste [52].

Therefore, in general, the environmental aspects of RE research are still very limited. It is to be expected that the emergence of new RE producers globally and the focus on environmental improvement in China will help to expand the available data and knowledge in this area.

2.3. Social

The social component of sustainability can be defined as those components relating to the physical and psychological well-being of humans within society. In this case we include both the individual and social network elements which could be separated—for example under a "five capitals" approach [53]. Recently socio-environmental issues of the health impacts of RE processing (from both radioactive and non-radioactive contamination) in areas of China has been raised as a major concern [45]. The question of whether sites that have been contaminated by rare earths mineral processing can be adequately rehabilitated to allow for other uses post-mining from a social sustainability perspective is linked to perceptions of health risks and the technical ability to rehabilitate contaminated sites. The potential for such impacts has also been one of the key drivers behind protests at the Lynas Corporation plant in Malaysia, partially fueled by the negative experiences that a previous rare earths processing site on the peninsula [54].

Social resistance to rare earths mining also stems from arguments about environmental justice and how processing sites are often more difficult to get permitted in developed countries and hence lead to their location in developing countries. Indeed, environmental regulation was one key reason for the closure of RE operation in the USA. Much of the resistance to the Lynas plant in Malaysia questioned whether the choice of Lynas to situate the site in Malaysia was for purely economic factors or because social resistance in Australia would have been far too great.

On the other hand, there can be a social argument made for rare earths development as a contribution towards developing a "green economy" [55,56]. The Malaysian industrial park in Kuantan has made this case in their branding of the initiative as part of national planning effort towards sustainability. Social perceptions of risk at the site level thus need to be balanced with broader national trajectory towards sustainable technology development in determining the social sustainability of the rare earths sector. Furthermore, recycling and service sector opportunities for this sector have much potential for development as technologies improve for micro-retrieval of the metals. There is likely to be less social resistance as efforts towards a circular economy for rare earths develops alongside their green economic uses in products.

Another cross-cutting element that could be placed largely in the social category is the lack of trained, experienced personnel outside of China [57]. The lack of mine production of RE outside of China over the past decade has led to not only a centralization of production but also to a centralization of skills—which is a hindrance to the design and operation of primary processing facilities in the rest of the world. This type of vulnerability has ramifications for the lead time to start-up new facilities, but could also affect both the economic operation and environmental optimization of new plants.

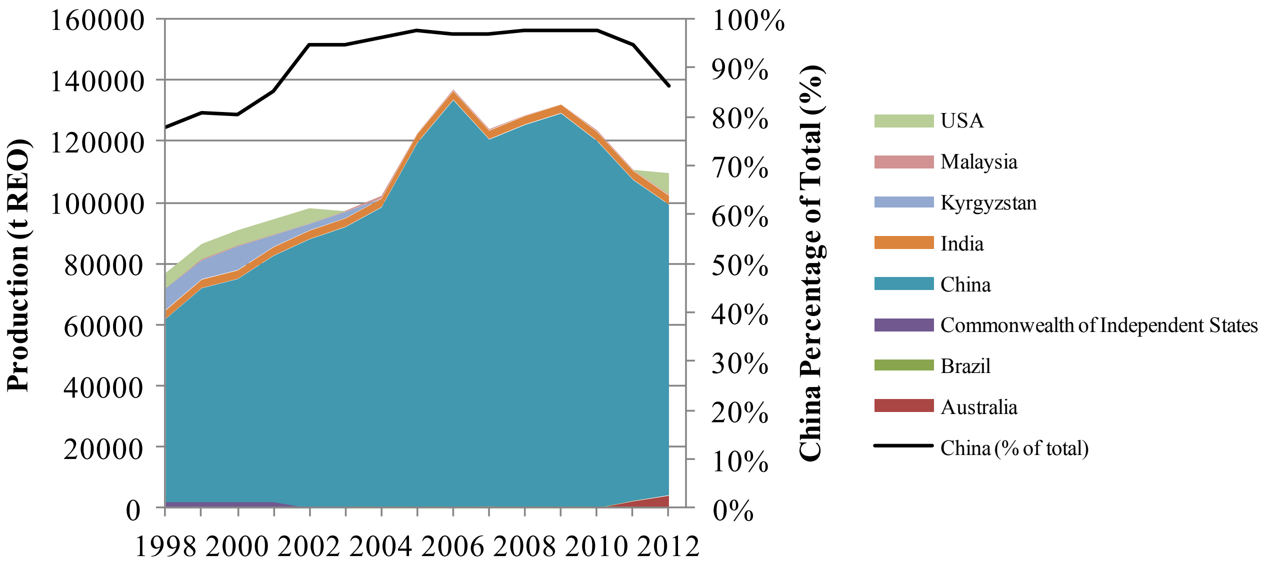
2.4. Economic

Research on the economic pillar of sustainability in RE has been focused on three key elements—the price of RE in the market (and its implication for technology costs), the restriction of supply by China (and its implications for price of RE and ability to roll-out new technology), and the availability of non-Chinese deposits. These elements reflect the concerns of governments and companies that rely on RE in their production lines.

The sudden export quota reduction (of 40%) by China (as the then 97% majority producer of RE) [58] sent a shock through the international community—with those especially concerned being the countries and companies that relied heavily on RE for economic production (Japan, USA and Europe). The quota reduction, in conjunction with additional environmental costs and the increase in demand due to clean energy technologies, subsequently produced dramatic increases in prices [36]. This has largely been the driver behind the recent policies on "critical" or "strategic" minerals [1,5].

Due to the concerns over centralization of supply in China, a concerted effort has been made in the development of alternative resources—both conventional resources available in other countries—e.g., Australia or USA—and in unconventional resources such as expanded recycling [22], coal and coal ash [49,59] and deep sea deposits [42,51,60]. The resulting investment in conventional resources has reduced Chinese dominance of the production of RE to 86% in 2012 (see Figure 1). The unconventional resources are still largely or entirely undeveloped—although Japan will examine the feasibility of production from deep sea deposits by 2018 [61], and some recycling is being commercially undertaken with significant research level initiatives [22]. There is no reliable estimate on the cost of such operations (although some positive claims are made [62]), or of the other aspects of sustainability, making a significant gap in knowledge for a rapidly opening area of study.

Figure 1. Production trends in rare earths—data source [40].



3. Discussion

From a sustainability perspective, the development of rare earths element deposits and mines and the subsequent application and use of rare earths in final products poses an interesting question: Do the sustainability benefits of products containing rare earths balance or outweigh the extraction and processing environmental and social impacts? As mentioned earlier in this paper, rare earth elements are performing an important function in our everyday lifestyle with use in a range of products. Such products include those that can make a significant contribution to improving energy efficiency and reducing greenhouse gas emissions, which is becoming increasing more important from a global standpoint. Yet, the extraction and processing of rare earths have impacts from both an environmental and social perspective. While mining of any ore body results in large volumes of waste, it is the association of radioactive elements thorium and uranium in the waste from mining rare earth elements that has caused most concern from an environmental and health aspect. There will continue to be ongoing debate about the intensity of the long term environmental and health impacts mining rare earth elements, and this debate will only add to the mix of issues that need to be dealt with in understanding the overall importance and contribution that rare earths makes to the sustainability of a country or globally. The balancing of these impacts against the benefits is critical to understanding the overall value in a sustainability sense (technical, environmental, social and economic) that can be derived from rare earths.

Over recent years there has been severe price fluctuations brought on, as described above, by the sudden export quota reduction (of 40%) by China. Volatility in metal prices can drive the exploration and development of new deposits or the investigation into alterative sources, either other cheaper materials that will perform the same function or recovering the same rare earth elements from end of life products through recycling. Given one country, China, is a greater than 85% majority producer of RE and the subsequent listing of rare earth elements as "critical" or "strategic" elements in USA, the EU and Japan, there is sufficient incentives to develop research programs that investigate these alternative opportunities.

Industrial ecology is a relatively new science [63] for moving industrial systems from open cycle to closed cycle where wastes are re-used, recycled or re-processed instead of being discharged or disposed to the environment. Such an approach for rare earths could not only bring environmental benefits, as impacts from secondary processing should be lower than from primary sources (as concluded by the life cycle assessment mentioned above [47], but also economic benefits, as end of life products that contain rare earth elements effectively become a new resource, or equivalent to an ore body in primary extraction and processing. This latter point produces a geopolitical ingredient to industrial ecology applications of rare earth elements as it creates an element of security of supply for rare earths. For countries that have to dispose of end of life products containing rare earths and do not have naturally occurring rare earth resources, understanding the mechanisms to enable substantially higher levels of recycling could feasibly be very attractive.

There must be technically feasible pathways for recovering rare earths from end of life products, however it is typically the non-technical barriers—such as legislative and regulatory systems, or the need for different industry sectors to willing cooperative, understanding the financial drivers for recycling, or diversification of business activities—that are more challenging and need specific attention to ensure that closing the cycling can be achieved. Greater understanding and appreciation of these barriers and associated enablers helps build a clearer picture of the mechanisms that could promote greater levels of rare earths recycling and reuse and the resulting related benefits, such as new industries, skills development, less environmental impact.

As with any sustainability assessment of a mineral or metal, there are compromises in weighing up the impacts along the value chain with the final benefits from the mineral's or metal's use and application. While rare earths are no different, the recent expansion of development activity in rare earths means that it will receive and is receiving greater focus on the potential detrimental impacts from this development. As stated earlier, little work has been undertaken to analyze the sustainability impacts and benefits in a structured and holistic manner of rare earths. Issues that can or might affect the development of resources need focused impact research in an effort to identify if they can address concerns of key and critical stakeholders and enable more sustainable production and use of rare earths. Figure 2 illustrates some of the key linkages and influences between the different areas of sustainability considered here, and an estimate of the level of development or performance in regards to both the knowledge base as well as the practical operation [at both the (a) primary production; and (b) the end-usage, ends of the supply chain]. Poor in this case indicates that either the impacts are highly negative (performance) or knowledge is either scarce or not well developed (knowledge), while "very good" represents either highly positive performance or very well understood (knowledge). (It must be noted that the evaluation of "poor" through to "very good" is the subjective evaluation of the authors based on this study of the literature.)

From the review analysis conducted and presented in this article, the authors believe the following topics of research that would benefit the rare earth industry over the coming years are:

- In-depth understanding of the long term health and environmental impacts associated with the mining and processing of rare earths;
- Identification of the key barriers and enabler for adopting an industrial ecology or closed cycle approach to use and re-use of rare earths;
- Economic analysis to comprehend the supply and demand for rare earths due to major price fluctuations and appearance of competitive alterative materials;
- Effect of regulatory and policy frameworks on more sustainable production, use and re-use of rare earths.

In order to try and address these gaps in knowledge, a number of emerging initiatives to link industry and academia are being funded, with research into the sustainability impacts and implications of these key materials as important elements of the research agenda.

Figure 2. Sustainability aspects, connections and level of development with regards to rare earths: (**a**) Primary production and (**b**) End usage.

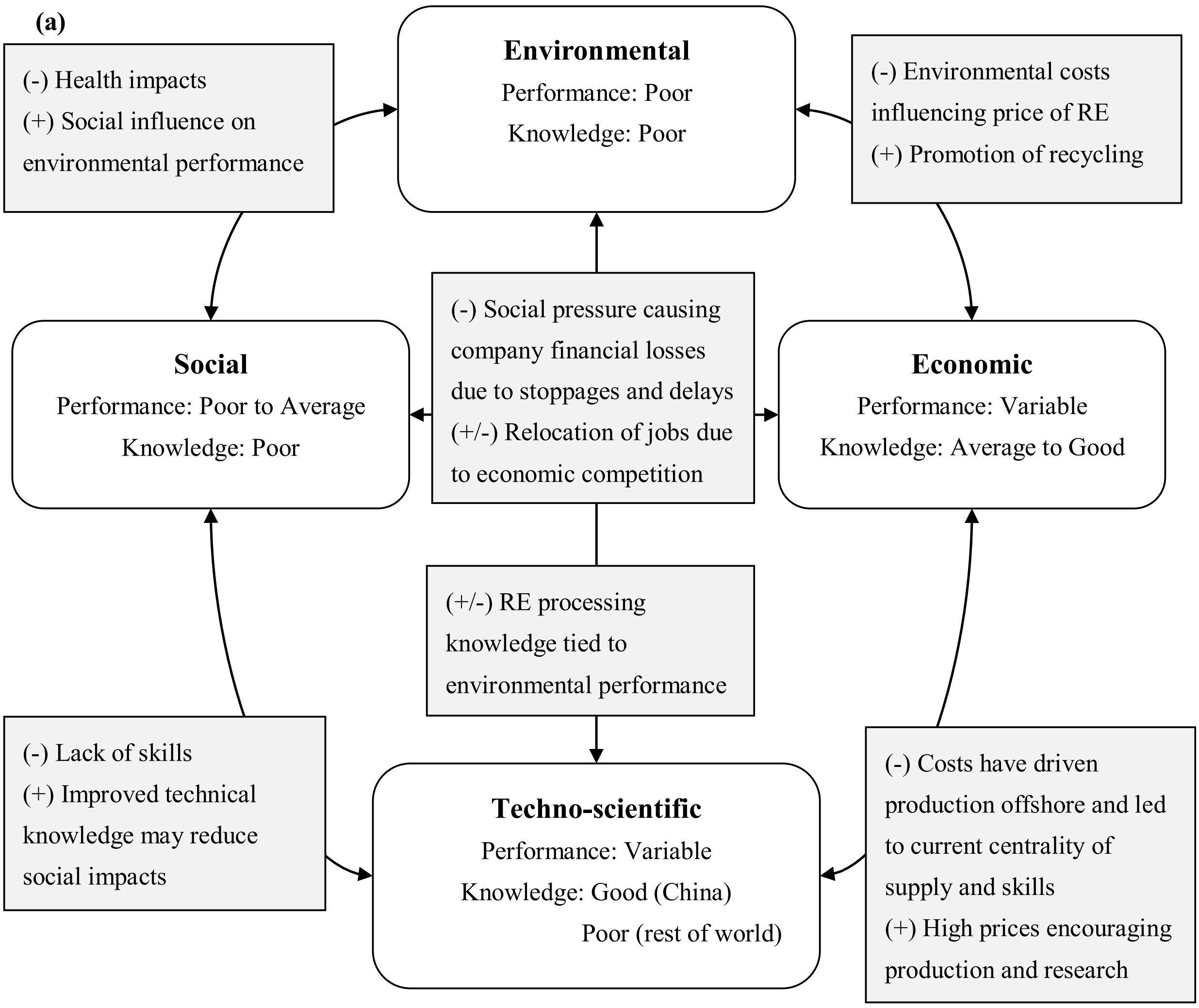
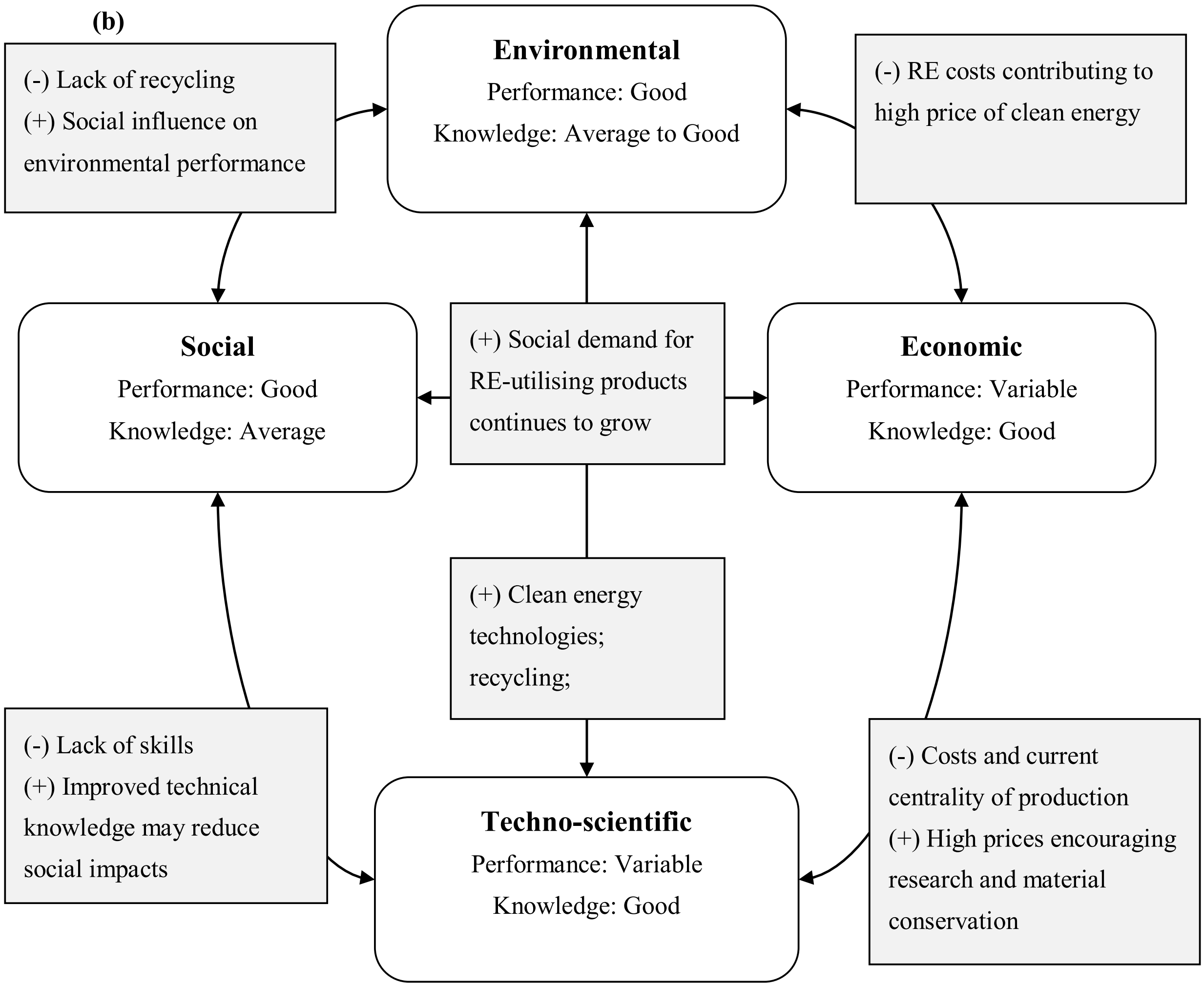


Figure 2. *Cont.*



4. Conclusions

This review has briefly addressed four key areas of sustainability in the RE industry: technical, environmental, social and economic. It highlights that there is no prior research that has addressed the wider sustainability impacts of RE across these multiple areas, leaving a significant gap in knowledge for future examination. The recent focus on RE due to the restriction of Chinese export quotas is likely to be beneficial in regards to expanding the knowledge base in this area, and a number of key initiatives have been commenced to address some of the sustainability concerns.

Acknowledgments

Funding for some of the authors' involvement in this work has been provided through the NextMine™ Initiative of the University of Queensland's Sustainable Minerals Institute.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Graedel, T.E. On the future availability of the energy metals. *Annu. Rev. Mater. Res.* **2011**, *41*, 323–335.
2. National Research Council. *Minerals, Critical Minerals, and the U.S. Economy*; National Academies Press: Washington, DC, USA, 2008.
3. Bauer, D.; Diamond, D.; Li, J.; Sandalow, D.; Telleen, P.; Wanner, B. *U.S. Department of Energy Critical Materials Strategy*; U.S. Department of Energy: Washington, DC, USA, 2010.
4. American Physical Society; The Materials Research Society. *Energy Critical Elements: Securing Materials for Emerging Technologies*: *A Report by the APS Panel on Public Affairs & the Materials Research Society*; American Physical Society: Washington, DC, USA, 2011.
5. Moss, R.L.; Tzimas, E.; Kara, H.; Willis, P.; Kooroshy, J. The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. *Energy Policy* **2013**, *55*, 556–564.
6. European Commission. Critical Raw Materials for the EU. In *Report of the Ad-Hoc Working Group on Defining Critical Raw Materials*; European Commission: Brussels, Belgium, 2010.
7. Japan Oil, Gas and Metals National Corporation Web Page. Rare Metals Stockpiling. Available online: http://www.jogmec.go.jp/english/stockpiling/stockpiling_015.html (accessed on 15 August 2013).
8. Cao, Z.G.; Li, Z.X.; Li, C.P.; Zhao, Y.Q.; Liu, Y. Current Issues and Policies on Energy Critical Element Sectors in China—A Global Perspective. In Proceedings of 2011 International Conference on Electrical and Control Engineering (ICECE); IEEE: New York, NY, USA, 2011.
9. Hurd, A.J.; Kelley, R.L.; Eggert, R.G.; Lee, M.-H. Energy-critical elements for sustainable development. *MRS Bull.* **2012**, *37*, 405–410.
10. Corder, G.D.; McLellan, B.C.; Bangerter, P.J.; van Beers, D.; Green, S.R. Engineering-in sustainability through the application of SUSOP®. *Chem. Eng. Res. Des.* **2012**, *90*, 98–109.
11. McLellan, B.; Zhang, Q.; Farzaneh, H.; Utama, N.A.; Ishihara, K.N. Resilience, sustainability and risk management: A focus on energy. *Challenges* **2012**, *3*, 153–182.
12. Borzone, G.; Raggio, R.; Ferro, R. Thermochemistry and reactivity of rare earth metals. *Phys. Chem. Chem. Phys.* **1999**, *1*, 1487–1500.
13. Gupta, C.K.; Krishnamurthy, N. *Extractive Metallurgy of Rare Earths*; CRC Press: Boca Raton, FL, USA, 2005.
14. Liao, C.S.; Wu, S.; Cheng, F.X.; Wang, S.L.; Liu, Y.; Zhang, B.; Yan, C.H. Clean separation technologies of rare earth resources in China. *J. Rare Earths* **2013**, *31*, 331–336.
15. Jordens, A.; Cheng, Y.P.; Waters, K.E. A review of the beneficiation of rare earth element bearing minerals. *Miner. Eng.* **2013**, *41*, 97–114.
16. Hirai, T.; Komasawa, I. Separation of rare metals by solvent extraction employing reductive stripping technique. *Miner. Process. Extr. Met. Rev.* **1997**, *17*, 81–107.
17. Zhang, Y.Q.; Li, J.N.; Huang, X.W.; Wang, C.M.; Zhu, Z.W.; Zhang, G.C. Synergistic extraction of rare earths by mixture of HDEHP and HEH/EHP in sulfuric acid medium. *J. Rare Earths* **2008**, *26*, 688–692.
18. Thakur, N.V. Separation of rare earths by solvent extraction. *Miner. Process. Extr. Met. Rev.* **2000**, *21*, 277–306.

19. Zhu, L.Y.; Duan, W.H.; Xu, J.M.; Zhu, Y.J. Extraction of actinides and lanthanides by supercritical fluid. *J. Eng. Gas Turbines Power* **2011**, *133*, 052903:1–052903:8, doi:10.1115/1.4002354.
20. Duan, W.H.; Cao, P.J.; Zhu, Y.J. Extraction of rare earth elements from their oxides using organophosphorus reagent complexes with HNO_3 and H_2O in supercritical CO_2. *J. Rare Earths* **2010**, *28*, 221–226.
21. Takahashi, Y.; Châtellier, X.; Hattori, K.H.; Kato, K.; Fortin, D. Adsorption of rare earth elements onto bacterial cell walls and its implication for REE sorption onto natural microbial mats. *Chem. Geol.* **2005**, *219*, 53–67.
22. Binnemans, K.; Jones, P.T.; Blanpain, B.; Gerven, T.V.; Yang, Y.X.; Walton, A.; Buchert, M. Recycling of rare earths: A critical review. *J. Clean. Prod.* **2013**, *51*, 1–22.
23. Schüler, D.; Buchert, M.; Liu, D.-I.R.; Dittrich, D.-G.S.; Merz, D.-I.C. Study on Rare Earths and Their Recycling. In *Final Report for The Greens/EFA Group in the European Parliament*; Öko-Institut e.V.: Freiburg, Germany, 2011.
24. Tanaka, M.; Oki, T.; Koyama, K.; Narita, H.; Oishi, T. Recycling of Rare Earths from Scrap. In *Handbook on the Physics and Chemistry of Rare Earths*; Bünzli, J.-C.G., Pecharsky, V.K., Eds; Elsevier: Amsterdam, The Netherlands, 2013; Chapter 255, pp. 159–211.
25. Xu, T.; Peng, H.Q. Formation cause, composition analysis and comprehensive utilization of rare earth solid wastes. *J. Rare Earths* **2009**, *27*, 1096–1102.
26. Gasser, M.S.; Aly, M.I. Separation and recovery of rare earth elements from spent nickel–metal-hydride batteries using synthetic adsorbent. *Int. J. Miner. Process.* **2013**, *121*, 31–38.
27. Resende, L.V.; Morais, C.A. Study of the recovery of rare earth elements from computer monitor scraps—Leaching experiments. *Miner. Eng.* **2010**, *23*, 277–280.
28. Ishii, M.; Matsumiya, M.; Kawakami, S. Development of recycling process for rare earth magnets by electrodeposition using ionic liquids media. *ECS Trans.* **2013**, *50*, 549–560.
29. Xu, T.; Zhang, X.D.; Lin, Z.; LÜ, B.Y.; Ma, C.M.; Gao, X.L. Recovery of rare earth and cobalt from Co-based magnetic scraps. *J. Rare Earths* **2010**, *28*, 485–488.
30. Vander Hoogerstraete, T.; Wellens, S.; Verachtert, K.; Binnemans, K. Removal of transition metals from rare earths by solvent extraction with an undiluted phosphonium ionic liquid: Separations relevant to rare-earth magnet recycling. *Green Chem.* **2013**, *15*, 919–927.
31. Yang, F.; Kubota, F.; Baba, Y.; Kamiya, N.; Goto, M. Selective extraction and recovery of rare earth metals from phosphor powders in waste fluorescent lamps using an ionic liquid system. *J. Hazard. Mater.* **2013**, *254–255*, 79–88.
32. Eliseeva, S.V.; Bunzli, J.-C.G. Rare earths: Jewels for functional materials of the future. *New J. Chem.* **2011**, *35*, 1165–1176.
33. Leonard, R.L.; Gray, S.K.; Albritton, S.D.; Brothers, L.N.; Cross, R.M.; Eastes, A.N.; Hah, H.Y.; James, H.S.; King, J.E.; Mishra, S.R.; *et al*. Rare earth doped downshifting glass ceramics for photovoltaic applications. *J. Non Cryst. Solids* **2013**, *366*, 1–5.
34. Atyaoui, M.; Dimassi, W.; Atyaoui, A.; Elyagoubi, J.; Ouertani, R.; Ezzaouia, H. Improvement in photovoltaic properties of silicon solar cells with a doped porous silicon layer with rare earth (Ce, La) as antireflection coatings. *J. Lumin.* **2013**, *141*, 1–5.
35. Hoenderdaal, S.; Espinoza, L.T.; Marscheider-Weidemann, F.; Graus, W. Can a dysprosium shortage threaten green energy technologies? *Energy* **2013**, *49*, 344–355.

36. Bradshaw, A.M.; Hamacher, T. Nonregenerative natural resources in a sustainable system of energy supply. *ChemSusChem* **2012**, *5*, 550–562.
37. Antolini, E.; Perez, J. The use of rare earth-based materials in low-temperature fuel cells. *Int. J. Hydrog. Energy* **2011**, *36*, 15752–15765.
38. Rahman, M.A. History of interior permanent magnet motors [History]. *IEEE Ind. Appl. Mag.* **2013**, *19*, 10–15.
39. Kiyota, K.; Sugimoto, H.; Chiba, A. Comparison of Energy Consumption of SRM and IPMSM in Automotive Driving Schedules. In Proceedings of the Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, USA, 15–20 September 2012; pp. 853–860.
40. United States Geological Survey (USGS). *Mineral Commodity Summaries 2013*; USGS: Washington, DC, USA, 2013.
41. Khadijeh, R.E.S.; Elias, S.B.; Wood, A.K.; Reza, A.M. Rare earth elements distribution in marine sediments of Malaysia coasts. *J. Rare Earths* **2009**, *27*, 1066–1071.
42. Kato, Y.; Fujinaga, K.; Nakamura, K.; Takaya, Y.; Kitamura, K.; Ohta, J.; Toda, R.; Nakashima, T.; Iwamori, H. Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements. *Nat. Geosci*. **2011**, *4*, 535–539.
43. Xue, P.Z.; Lin, J.F. Discussion on the Rare Earth Resources and Its Development Potential of Inner Mongolia of China. In Proceedings of 2011 International Conference on Materials for Renewable Energy & Environment (ICMREE), Shanghai, China, 20–22 May 2011.
44. Arafura Resources Limited. *Nolans Project Update*; Arafura Resources Limited: Perth, Australia, 2012.
45. Hurst, C. *China's Rare Earth Elements Industry: What Can the West Learn?*; DTIC Document; Institute for the Analysis of Global Security: Washington, DC, USA, 2010.
46. Yang, X.J.; Lin, A.J.; Li, X.-L.; Wu, Y.D.; Zhou, W.B.; Chen, Z.H. China's ion-adsorption rare earth resources, mining consequences and preservation. *Environ. Dev.* **2013**, doi:10.1016/j.envdev.2013.03.006.
47. Tharumarajah, R.; Koltun, P. Cradle to Gate Assessment of Environmental Impact of Rare Earth Metals. In Proceedings of the 7th Australian Conference on Life Cycle Assessment, Melbourne, Australia, 9–10 March 2011; Australian Life Cycle Assessment Society: Melbourne, Australia, 2011.
48. Morf, L.S.; Gloor, R.; Haag, O.; Haupt, M.; Skutan, S.; Lorenzo, F.D.; Böni, D. Precious metals and rare earth elements in municipal solid waste—Sources and fate in a Swiss incineration plant. *Waste Manag.* **2013**, *33*, 634–644.
49. Mayfield, D.B.; Lewis, A.S. Environmental Review of Coal Ash as a Resource for Rare Earth and Strategic Elements. In Proceedings of the 2013 World of Coal Ash (WOCA) Conference, Lexington, KY, USA, 22–25 April 2013; The University of Kentucky: Lexington, KY, USA, 2013.
50. McLellan, B.C.; Williams, R.P.; Lay, J.; van Riessen, A.; Corder, G.D. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *J. Clean. Prod.* **2011**, *19*, 1080–1090.
51. Hein, J.R.; Mizell, K.; Koschinsky, A.; Conrad, T.A. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geol. Rev.* **2013**, *51*, 1–14.

52. Kamei, T. Recent research of thorium molten-salt reactor from a sustainability viewpoint. *Sustainability* **2012**, 4, 2399–2418.
53. Forum for the Future Web Page. The Five Capitals. Available online: http://www.forumforthefuture.org/project/five-capitals/overview (accessed on 12 September 2011).
54. Ichihara, M.; Harding, A. Human rights, the environment and radioactive waste: A study of the Asian rare earth case in Malaysia. *Rev. Eur. Community Int. Environ. Law* **1995**, *4*, 1–14.
55. Akademi Sains Malaysia; Majlis Profesor Negara. *Rare Earth Industries: Moving Malaysia's Green Economy Forward*; Akademi Sains Malaysia, Academy of Sciences, Malaysia: Kuala Lumpur, Malaysia, 2011.
56. Malaysian Academy of Science. *Revitalizing the Rare Earths Mineral Programme in Peninsular Malaysia as a Strategic Industry*; Akademi Sains Malaysia: Kuala Lumpur, Malaysia, 2013.
57. Gschneidner, K.A., Jr. The rare earth crisis—The supply/demand situation for 2010–2015. *Mater. Matters* **2012**, *6*, Article 2.
58. Gu, B. Mineral export restraints and sustainable development—Are rare earths testing the WTO's loopholes? *J. Int. Econ. Law* **2011**, *14*, 765–805.
59. Seredin, V.V.; Dai, S.F.; Sun, Y.Z.; Chekryzhov, I.Y. Coal deposits as promising sources of rare metals for alternative power and energy-efficient technologies. *Appl. Geochem.* **2013**, *31*, 1–11.
60. Cui, Y.C.; Liu, J.H.; Ren, X.W.; Shi, X.F. Geochemistry of rare earth elements in cobalt-rich crusts from the Mid-Pacific M seamount. *J. Rare Earths* **2009**, *27*, 169–176.
61. Government of Japan. *Basic Plan on Ocean Policy*; Headquarters for Ocean Policy, Government of Japan: Tokyo, Japan, 2013.
62. Joshi, P.B.; Preda, D. A Low-Cost Rare Earth Elements Recovery Technology. In Proceedings of the 2013 World of Coal Ash (WOCA) Conference, Lexington, KY, USA, 22–25 April 2013.
63. Frosch, R.A.; Gallopoulos, N.E. Strategies for manufacturing. *Sci. Am.* **1989**, *261*, 144–152.